Laser Produced Plasma Light Source for EUVL

Igor V. Fomenkov*, Alex I. Ershov, William N. Partlo, David W. Myers
Richard L. Sandstrom, Norbert R. Böwering, Georgiy O. Vaschenko, Oleh V. Khodykin, Alexander N. Bykanov, Shailendra N. Srivastava, Imtiaz Ahmad, Chirag Rajyaguru, Daniel J. Golich, Silvia De Dea, Richard R. Hou, Kevin M. O'Brien, Wayne J. Dunstan, David C. Brandt

Cymer Inc., 17075 Thornmint Court, San Diego, CA 92127, USA

ABSTRACT

This paper describes the development of laser-produced-plasma (LPP) extreme-ultraviolet (EUV) source architecture for advanced lithography applications in high volume manufacturing. EUV lithography is expected to succeed 193nm immersion technology for sub-22nm critical layer patterning. In this paper we discuss the most recent results from high EUV power testing and debris mitigation testing on witness samples and normal incidence collectors. Subsystem performance will be shown including the CO2 drive laser, debris mitigation, normal incidence collector and coatings, droplet generation, laser-to-droplet targeting control, intermediate-focus (IF) metrology and system use and experience. In addition, a number of smaller lab-scale experimental systems have also been constructed and tested. This presentation reviews the experimental results obtained on systems with a focus on the topics most critical for an HVM source.

Keywords: EUV source, EUV lithography, Laser Produced Plasma

1. INTRODUCTION

EUV Lithography is the front runner for next generation critical dimension imaging after 193 nm immersion lithography for layer patterning below the 32 nm node; beginning in 2013 according to the International Technology Roadmap for Semiconductors (ITRS). NAND Flash devices are expected to have the need for this manufacturing technology as soon as 2011, with pilot line system introduction starting this year (2010). The availability of high power 13.5 nm sources has been categorized as high risk and ranked as critical with other technologies requiring significant developments to enable the realization of EUV lithography. High sensitivity photoresists with good line-edge-roughness (LER) and line-width-roughness (LWR) are needed to keep the required source power within reasonable limits. Photoresist sensitivity and other light absorbing elements are the basis to derive EUV source power requirements within the usable bandwidth (BW) of 2 %. Scanner manufacturers are requiring clean EUV power close to 200W at the intermediate focus (IF) to enable > 100 wph scanner throughput assuming 10 mJ/cm^2 photoresist sensitivity. The need for a Spectral Purity Filter (SPF) increases the requirements for Raw EUV Power even higher. Clean EUV Power is calculated by taking the Raw EUV power and subtracting the losses associated with the Spectral Purity Filter (SPF) and dose control, for initial sources these losses are estimated to be 35% and 20% respectively. A scalable EUV source architecture is needed to enable the evolution of EUV lithography during the life cycle of the technology. Laser-produced-plasma (LPP) sources are expected to deliver the necessary high power for critical-dimension high-volume manufacturing (HVM) scanners for the production of integrated circuits in the post-193 nm immersion era.[1]

The LT1 source is shown in Figure 1. The ETS has been used since mid 2006 to develop CO_2 laser and tin droplet LPP technology [2]. Many development milestones have been reported from this source and even today it is still being used to test our latest improvements to the overall source architecture. The most recent change was the addition of a fourth amplifier to the CO2 laser to boost the laser power to near 20kW. It operates using the same 30 micron diameter droplets as our production sources. Preformance results of test and prototype sources were discussed in detail

Extreme Ultraviolet (EUV) Lithography, edited by Bruno M. La Fontaine, Proc. of SPIE Vol. 7636, 763639 · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.848408

previously [3,4,5]. An HVM I source is shown in Figure 2. We have six sources in production with the first three in the final stages of integration and the first one entering test. The HVM I sources use a 5sr normal incidence collector, 30 micron tin droplets and a ~20kW CO_2 laser. The HVM I source is shown in its inclined position of 27 degrees as it is positioned when integrated into the scanner.

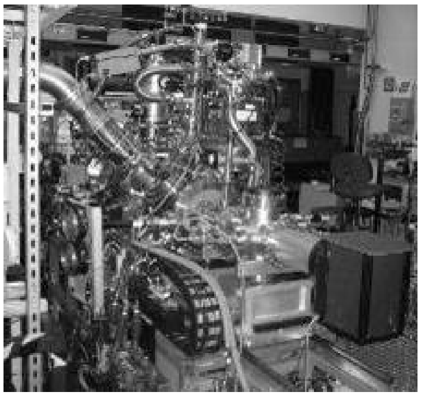

Figure 1: LT1

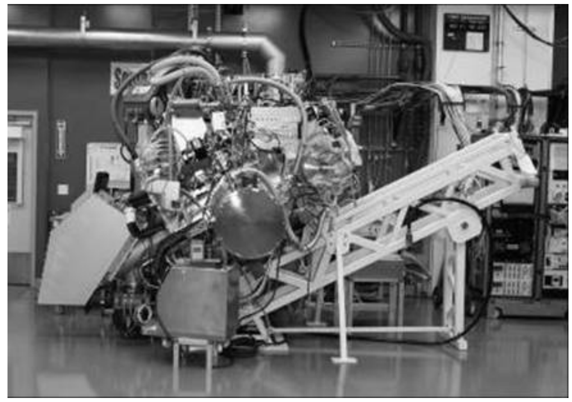

Figure 2: HVM I Source in Production

2. EUV POWER

EUV power technology has been developed on our LT1 source using the same architecture as our production sources but with very flexible designs to allow for rapid prototyping and to apply new learning as fast as possible. The most recent power results are shown in Figure 3 and Figure 4. Both of these results were obtained using 30 micron diameter droplets and a burst duration of 400ms while firing the laser to hit every droplet during the burst. A 10ms sliding window is plotted through the data to show the inherent open loop dose variation. Applying dose control to this level of performance would change the power to the lowest point on this curve, or about 80W.

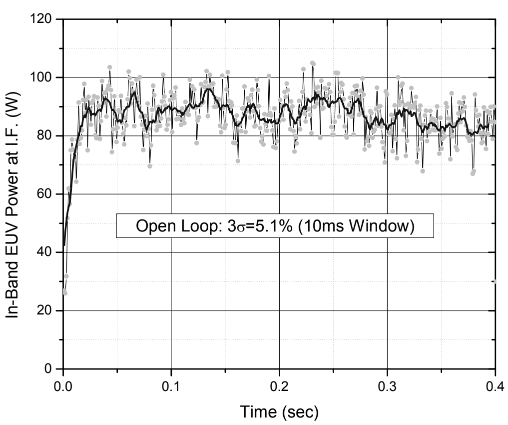

Figure 3: Raw EUV power @ IF at 40% duty cycle

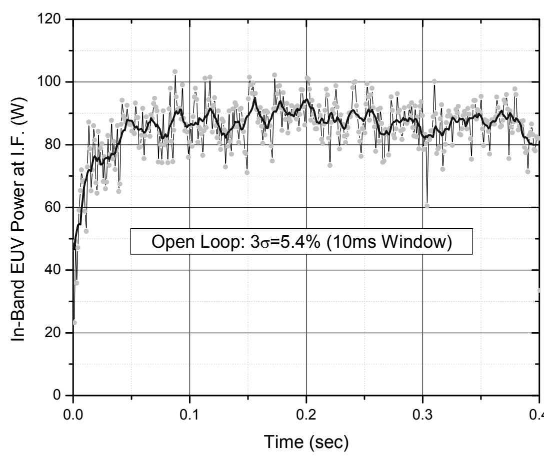

Figure 4: Raw EUV power @ IF at 80% duty cycle

When dose control is applied to the source the stability of the output power meets the requirements set fourth by scanner manufacturers. Figure 5 shows the open loop stability of the EUV output power just before applying the dose control

algorithm, Figure 6 is the stabilized performance during the same run when the algorithm is actively controlling the power output by applying feedback from energy sensors on the source. A dose stability of 3σ<±0.35% was achieved.

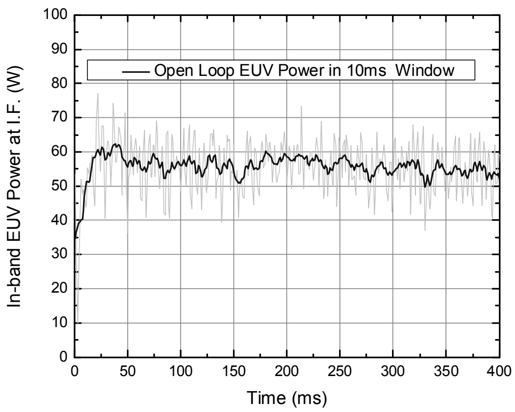

Figure 5: Raw EUV power @ IF at 60% duty cycle

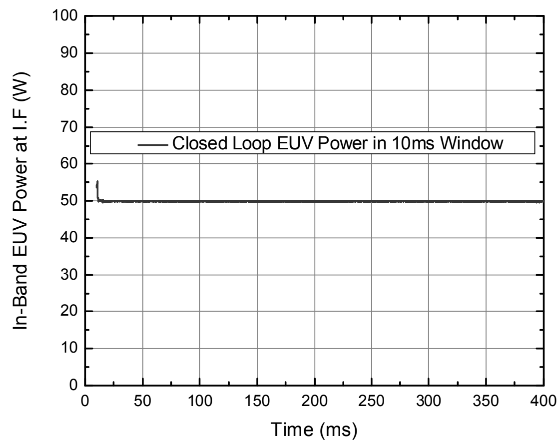

Figure 6: Dose stabilized EUV power @ IF at 60% duty cycle

3. NORMAL INCIDENCE COLLECTORS

Cymer's LPP EUV source employs near-normal-incidence mirrors with a very large solid angle for light collection. Such a geometry has numerous advantages, which has been discussed elsewhere.[6] As we reported earlier[1], the complete infrastructure is in place for manufacturing of large-size normal-incidence collector mirrors. For demonstration of the light collection capabilities of our source several 1.6 sr sub-aperture versions (300 mm optical diameter) have been produced and used in the development system for testing. Several large (> 650 mm diameter) HVM I 5sr collectors are now also completed. The collectors have been coated with graded multilayer coatings with layer periods optimized for high EUV reflectance at the corresponding incidence angles.

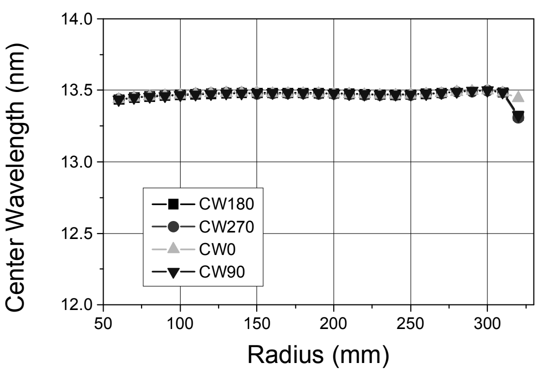

Figure 7: Center wavelength of points measured on four radial lines of a 5sr normal incidence collector mirror after multi-layer coating.

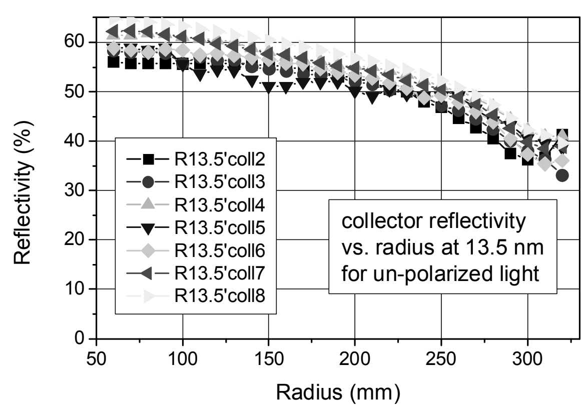

Figure 8: Reflectivity of several 5sr collectors for un-polarized light as a function of mirror radius. The data were determined from measurements with s-polarized EUV light at 13.5nm (PTB) and by scaling according to samples measured with both s-polarized and un-polarized light.

Figure 7 shows the center wavelength of a MLM coated 5sr collector. It is matched well to 13.5 nm wavelength for all radial positions on the mirror. Figure 8 displays the EUV reflectance at 13.5 nm wavelength obtained as a function of radial position for several 5sr mirrors, determined corresponding reflectance values for incidence of unpolarized light as derived from results obtained with test samples at different radial positions. When taking into account the contributing reflecting area, the reflectance for unpolarized light at 13.5 nm corresponds to an average value of >50 %.

4. DROPLET GENERATOR

The droplet generator provides a constant stream of liquid tin targets (droplets) to the focal point of the collector where the CO_2 laser pulse is used to create the light-emitting plasma. The main requirement for the generators is to produce reproducibly small droplet targets of identical size at the repetition rate of the laser pulses (typically 50 kHz) [7] Droplets with high temporal and spatial stability have been consistently produced over hundreds of hours of operation time, with the duration mainly limited by the capacity of the tin reservoir vessel. The longest continuous run of the droplet generator achieved so far is in excess of 500 hours. Figure 9 shows the position stability of 16 µm diameter droplets when the stream is propagating in a horizontal direction. Short-term position stability is better than 1 µm. The slow position drift can be compensated by the active position control system as was demonstrated separately.

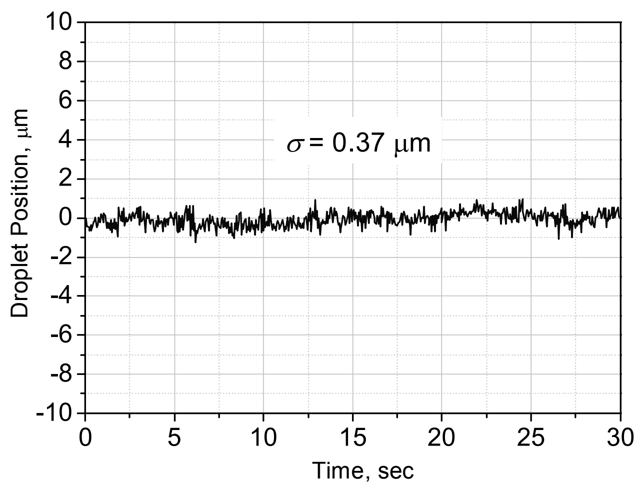

Figure 9: Position stability of 16 µm droplets.

We have developed the technology for generating droplets with diameter of ~16 µm. These droplets meet the stability and timing requirements for the present system, as was tested during 200 hours of operation without failure. Droplet size reduction leads to a significant efficiency increase for debris mitigation technologies. Second generation sources should have droplet diameters further reduced to these sizes. When droplets of this size are generated at a frequency of 50 kHz, about 1 liter of tin is consumed per year.

5. DEBRIS MITIGATION

Our debris mitigation system works by the use of hydrogen buffer gas to stop high energy fast ions and to remove tin deposition at a rate faster than it is deposited, or zero net deposition. Hydrogen buffer gas ability to stop tin ions has been described previously [3], and is shown in Figure 10. As the buffer gas pressure is increased both the ion energy and ion flux reaching the surface of the collector is reduced significantly. This technique has been previously shown to keep witness samples free of ion erosion and tin deposition[3].

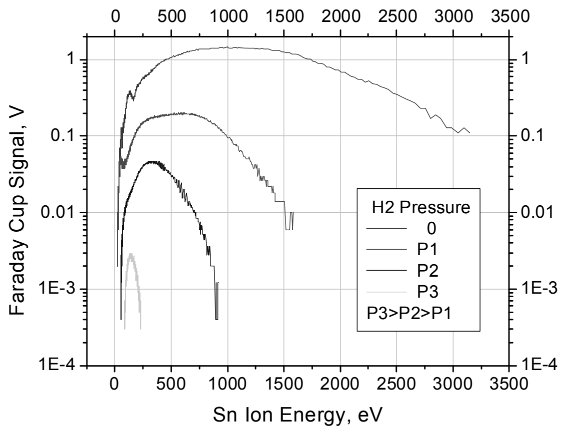

Figure 10: Hydrogen buffer gas pressure vs. ion energy and flux at the location of the collector surface

Hydrogen buffer gas debris mitigation was tested on a 5 sr collector in a prototype source that was subsequently shipped to a leading scanner manufacturer. The 5 sr collector was kept free of both erosion and deposition over a 9 hour period or about 600 million pulses[5]. The test was performed on 30 micron diameter droplets using 400ms burst duration at 40% duty cycle and EUV output power of ~15W at IF. Figure 11 shows a far field image of the EUV distribution and collector reflectivity after 2 hours. These images were taken with a fluorescence converter and CCD camera behind IF. Figure 12 shows the same collector after 9 hours of exposure with no change to the image quality.

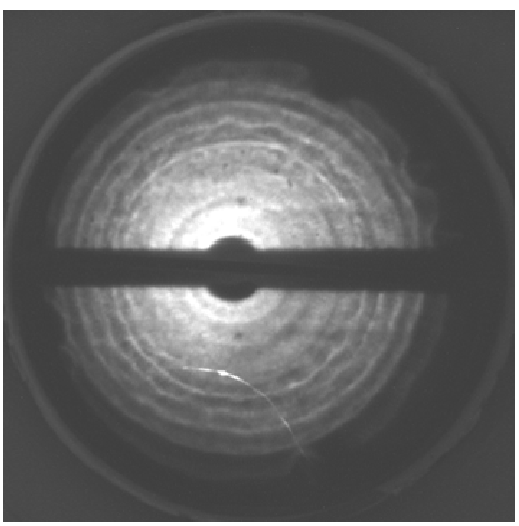

Figure 11: Far field image of EUV distribution and collector reflectivity after 2 hours of exposure

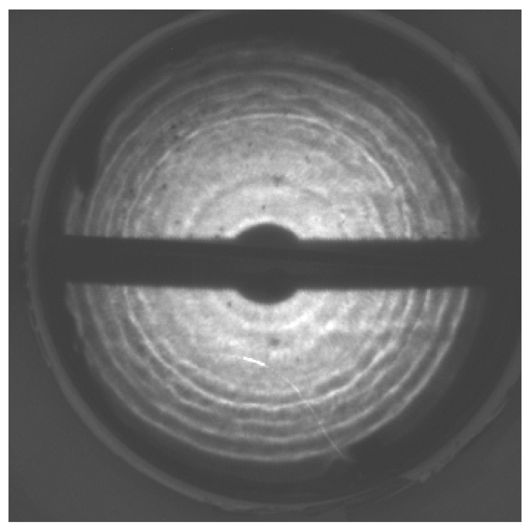

Figure 12: Far field image of EUV distribution and collector reflectivity after 9 hours of exposure

6. SUMMARY

Laser-produced plasma has been shown to be the leading source technology with scalability to meet requirements from leading scanner manufacturers and provide a path toward higher power as the lithography tools evolve over their life cycle. EUV power exceeding 90W at intermediate focus at 80% duty cycle and 400ms burst length has been reported. Normal-incidence collector mirrors of diameter > 650mm, with > 5 sr light collection and average reflectivities >50%

are produced and integrated into production LPP systems. LPP EUV source system manufacturing has progressed well. The high-conversion-efficiency combination of 10.6 µm laser radiation and Sn source element has been demonstrated with CE in excess of 3 %. EUV lithography is expected to be the critical dimension imaging solution in the post-193 nm immersion era. LPP source technology with power levels exceeding 400W is expected to enable the IF power requirement projected in the future, and to provide the much needed margin for photoresist sensitivity, spectral purity filters, optics degradation, process latitude, and overall equipment throughput. Cymer plans the commercialization of EUV light sources in 2010. The company continues to meet its EUV source development commitments to industry, customers and suppliers.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the valuable contributions from Martin J. Neumann and David N. Ruzic of University of Illinois, Urbana Champaign, Marco Perske, Hagen Pauer, Mark Schürmann, Sergiy Yulin, Torsten Feigl and Norbert Kaiser of Fraunhofer Institut f. Angewandte Optik und Feinmechanik, Eric Gullikson and Farhad Salmassi of Lawrence Berkeley National Laboratory, Frank Scholze, Christian Laubis, Christian Buchholz and coworkers at PTB, and Mark Tillack and Yezheng Tao of the University of California at San Diego. We are also very thankful for the invaluable support and contributions, past and present, of many scientists, engineers and technicians involved in the EUV technology program at Cymer.

REFERENCES

[1] I. V. Fomenkov, D. C. Brandt, A. N. Bykanov, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Böwering, G. O. Vaschenko, O. V. Khodykin, J. R. Hoffman, E. Vargas L., R. D. Simmons, J. A. Chavez, C. P. Chrobak, in: *Proc. of SPIE Vol.* ***6517****, Emerging Lithographic Technologies XI,* M. J. Lercel, ED., 65173J (2007).

[2] D. C. Brandt, I. V. Fomenkov,, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Böwering, A. N. Bykanov, G. O. Vaschenko, O. V. Khodykin, J. R. Hoffmann, E. Vargas L., R. D. Simmons, J. A. Chavez, C. P. Chrobak, in: *Proc. of SPIE Vol.* ***6517****, Emerging Lithographic Technologies XI,* M. J. Lercel, ED., 65170Q (2007).

[3] D. C. Brandt, I. V. Fomenkov, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Böwering, N. R. Farrar, G. O. Vaschenko,O. V. Khodykin, A. N. Bykanov, J. R. Hoffman, C. P. Chrobak, S. N. Srivastava, I. Ahmad, C. Rajyaguru, D.J. Golich, D. A. Vidusek, S. De Dea, R. R. Hou, in: *Proc. of SPIE Vol.* ***7271****, Alternative Lithographic Technologies,* F. M. Schellenberg, B. M. La Fontaine, Eds., 727103, (2009).

[4] I. V. Fomenkov, D. C. Brandt, A. N. Bykanov, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Böwering, N. R. Farrar, G. O. Vaschenko, O. V. Khodykin, J. R. Hoffman, C. P. Chrobak, S. N. Srivastava, D.J. Golich, D. A. Vidusek, S. De Dea, R. R. Hou, in: *Proc. of SPIE Vol.* ***7271****, Alternative Lithographic Technologies*, F. M. Schellenberg, B. M. La Fontaine, Eds., 727138 (2009).

[5] N. R. Böwering, I. V. Fomenkov, D. C. Brandt, A. N. Bykanov, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Farrar, G. O. Vaschenko, O. V. Khodykin, J. R. Hoffman, C. P. Chrobak, S. N. Srivastava, I. Ahmad, C. Rajyaguru, D.J. Golich, D. A. Vidusek, S. De Dea, R. R. Hou, Journal of Micro/Nanolith. MEMS MOEMS 8(4), 041504 (2009).

[6] N. R. Böwering, A. I. Ershov, W. F. Marx, O. V. Khodykin, B. A. M. Hansson, W. N. Partlo, E. Vargas L., J. A. Chavez, I. V. Fomenkov, D. W. Myers, D. C. Brandt, in: *Proc. of SPIE Vol.* ***6151****, Emerging Lithographic Technologies X,* M. J. Lercel, Ed., 61513R (2006).

[7] J. M. Algots, O. Hemberg, A. Bykanov, in: *Proc. of SPIE Vol.* ***5751****, Emerging Lithographic Technologies IX,* R. S. Mackay, Ed., 248-259 (2005).